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Artificial cooling of the atmosphere—A discussion on the environmental effects

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ABSTRACT

This article presents a literature review to discuss some new technological options for climate change mitigation called as Geoengineering and the environmental impacts related to aerosol emissions. Some proposals to produce a cooler effect in the Earth surface at short term are defending the injection of a large quantity of aerosol particles in the stratosphere like a "virtual Pinatubo". In 15 June 1991 a volcanic eruption of the Pinatubo Mount in Philippines resulted in around −0.5 °C variation in Earth surface temperature in 1992 and only in 1995 the temperature returned back to the former one. Several important environmental issues arise from this kind of mitigation proposal. Some of the topics which may be considered relevant in such analysis are: the level of acceptable risk of this kind of technological option for the human and the environment as a whole; the foreseen linear and non-linear impacts resultant from the artificial cooling effect in the Earth surface; the feasibility and cost-effectiveness of this kind of proposals. The environmental problems associated to aerosols injections into the stratosphere are the main topic discussed in the present article.

Contents

1. Introduction

Some proposals recently emerged in the international scientific publications about the production of a cooler effect in the Earth surface at short-term injecting in the stratosphere a huge quantity of aerosol particles like a "virtual Pinatubo". In 15 June 1991 a volcanic eruption of the Pinatubo Mount in Philippines resulted in around −0.5 °C variation in Earth surface temperature in 1992 and only in 1995 the temperature returned back to the former value. According to one of the proponents, Paul Crutzen, "the issue has come to the forefront, because of the dilemma facing international policy makers, who are confronted with the task to clean up air pollution, while simultaneously keeping global climate warming under control" [1].

Another author, in the same direction, Tom Wigley, analyzes whether the idea of injecting sulfates into the stratosphere could reduce global warming allowing more time for society to reduce the emissions of carbon dioxide. "A relatively modest geoengineering investment could reduce the economic and technological burden on mitigation by deferring the need for immediate or near-future cuts in carbon dioxide emissions." [2]. "Geoengineering could provide additional time to address the economic and technological challenges faced by a mitigation-only approach" [2].

Research's initiatives to consider whether it would be feasible to artificially enhance the albedo of the planet Earth to counteract greenhouse warming need to be deeper analyzed. The enhancement of albedo would be achieved by intentionally injecting sulfur into the stratosphere. These proposals are inspirited in the observed cooling of the atmosphere following two volcanic eruptions, El Chichon in 1984 and Mount Pinatubo in 1991 [3]. Nevertheless, several regional and local environmental problems resulted as consequences of these emissions.

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2. GHG and aerosol emissions

To avoid the danger of anthropogenic interference with the climate system, it was assigned an agreement under the UN Framework Convention on Climate Change, in 1992. Nevertheless, the international limits for emissions are still in process of discussion while new alternative proposals, so-called geoengineering, emerge in the climate scientific literature. The artificially enhanced albedo is seen as a response to the view that worldwide agreements for GHG emission reductions may not prove to be effective. Nevertheless, the proposal to offset the warming influence by injecting aerosols can result in deleterious health effects.

For both proposals, GHG emission reductions and aerosol injections, the issues in focus are the same: changes in the climate and atmospheric composition. In one case, the objective is to reduce the rates of fossil fuel and biomass burning, while for the other, it is to inject aerosol particles in the atmosphere but controlling the emissions so far.

The global climate models being developed by some research centers, such as the Hadley Center, have been dealing with different approaches for studying the global climate system. Recently, one of the most important discussions about climate system modeling is the inclusion of new non-linearity processes, expressing the complexity of the atmospheric behavior, related to the emissions of greenhouse gases and the consequent cumulative process. The majority of the studies are trying to define which non-linearity processes are fundamental and necessary for representing the climate system in an adequate way, in a feasible manner.

One non-linearity that seems to be important to be taken into account, in global climate models, is the consideration of the aerosol effects. This is due to the fact that they may result in large differences in the contributions to global climate change, between the different regions on the planet and for different periods of time. Other important issue regarding aerosols is that they may cause opposite effects: a cooling and a warming effect. For example, aerosols emitted by the burning of biomass may behave differently than the aerosols emitted by a volcano, due to their specific characteristics.

Aerosol emissions have largely increased since the beginning of the Industrial Revolution, on the same way as the concentration of carbon dioxide (CO_2) and other greenhouse gases (eg. methane nitrous oxide and chlorofluorocarbons—CFCs). The development of aerosol research involving their fundamental properties and effects on climate has been in debate for many years. During the 1960s, despite attention was mainly centered on greenhouse warming effects caused by the industrial emissions of CO_2, the capacity of atmospheric aerosols to affect the radiative balance of the Earth was considered by McCormick and Ludwig [4]. It can be pointed out that since the aerosols could absorb and scatter solar radiation, they could as well be responsible for heating or cooling the Earth's atmospheric system.

By the 1970s, attention on atmospheric problems was focused mainly on the depletion of the stratospheric ozone layer. In 1974, atmospheric chemists Molina and Rowland called the attention about the possible adverse impacts on stratospheric ozone by CFCs. During this period less attention was focused on greenhouse gases, aerosols and their effects on climate, however, some research was still performed, which investigated the direct and indirect effects of atmospheric aerosols. Schneider [5] developed a model and demonstrated that aerosol absorption could cause a heating of the atmosphere for a fixed amount of backscatter. Model results of Rasool and Schneider [6] estimated that the dust concentration in the atmosphere could have doubled during a century, and that it could double again in the next fifty years. This could cause a cooling of the Earth's surface, with a decrease in the mean temperature by as much as 3.5 K. It was then declared "*If sustained over a period of several years, such a temperature decrease could be sufficient to trigger an ice age*". In extensive studies, Twomey [7,8] described that an increase in anthropogenic emissions of aerosols could result in additional cloud condensation nuclei (CCN), which could produce higher concentrations of cloud droplets and, consequently, increase the albedo. This was defined as the first indirect effect and so called the "Twomey effect". Joseph [9] pointed out that the aerosol radiative effects can impact on the dynamics of the energy and momentum of the atmosphere, which may lead to changes in wind velocities and in the global circulation.

In the 1980s, the impacts on the climate induced by a doubling of the CO_2 concentration, and the subsequent increase in the global temperature, was a main concern in scientific research [10,11]. However, attention was again directed towards the aerosols and their effect on climate. Grassl and Newiger [12] showed that the aerosols play an important role in shortwave radiative transfer, both for clear and cloudy areas. They pointed out that the refractive index of the particulates, the albedo in the clear areas and the optical thickness of the clouds in the cloudy areas were the main parameters which influenced the variation in the energy budget. Izrael [13] suggested that an increase in sulfate aerosols could affect the radiative budget of the Earth, leading to accelerated cloud formation. He also pointed out that the existence of the stratospheric sulfate layer could result in increased stratospheric temperatures and changes in weather and climate.

In the course of the 1990s, studies of the anthropogenic impact on climate became more usual. One of the most important aspects was the contribution of the anthropogenic emissions to the greenhouse effect. In 1992 it was carried out the Rio Earth Summit, in the city of Rio de Janeiro, Brazil, and the United Nations Framework Convention on Climate Change (UNFCCC) was opened for signature. The main objective was to call for the reduction of greenhouse gases emissions from human activities. The final document included, in its first article – definitions, an explicit mentioning about particulates: *(8) "Sink" means any process, activity or mechanism which removes a greenhouse gas, an aerosol or a precursor of a greenhouse gas from the atmosphere and (9) "Source" means any process or activity which releases a greenhouse gas, an aerosol or a precursor of a greenhouse gas into the atmosphere*" [14].

In the early 1990s, calculations showed that sulfate aerosols could be cooling the atmosphere by scattering incoming solar radiation and causing an increase in cloud formation [15]. It was also called the attention to volcanic eruptions, which emitted many tons of sulfates into the higher atmosphere and resulted in the radiative cooling of the climate system [16]. More recently, Andronova and Schlesinger [17] have called the attention on the importance of considering the sulfate aerosols and their cooling effects into the discussion of responsibilities on global warming, as the greenhouse gas (GHG) emissions may be largely offset by the sulfate aerosol emissions.

The IPCC (Intergovernmental Panel on Climate Change) has treated the effects of aerosols on climate change in its periodic Assessment Reports [18]. The last IPCC report calls the attention to several aerosol issues, as for example: the need for characterization of chemical and physical properties; the investigation of aerosol species other than sulfate; the need for more measurements and models; the analysis of the uncertainties in the different factors needed to estimate direct forcing; the aerosol indirect effects on clouds, among others.

An important tool in improving the understanding of the complex dynamics of the atmosphere is a general circulation model (GCM). GCMs are used to study the climate of the past [19], the climate of the present, and future climate projections. Most of the GCMs that were employed until now took into account only the effects resulting from GHG emissions [20–22]. However, in

recognition of the growing importance of the effects of atmospheric aerosols on climate change, more recent GCM simulations have incorporated the aerosols and their effects on climate forcing [23–25].

3. Atmospheric aerosols and environmental impacts

Atmospheric aerosols are a complex mixture of substances from numerous sources, such as sulfate and black carbon. In general, their characterization involves the specification of their spatial and temporal concentration distribution, chemical composition, particle size distribution and some other properties such as morphology and index of refraction. Tropospheric aerosols have short lifetimes, display a large spatial variability and may affect climate on a regional and global scale. Atmospheric aerosols may be classified into primary and secondary particles, based on its origin and formation processes. Primary particles are emitted directly into the atmosphere, either by natural or anthropogenic sources. Several approaches may be employed in characterizing the aerosols and their effects on climate, like the experimental measurements in the neighborhood of the sources, the use of satellite data and the inclusion of aerosol processes in climate modeling.

Atmospheric aerosols tend to have their greatest influence on the local and regional levels (energy balance and chemistry). The most common primary aerosols in the troposphere are: sea salt, soil dust (or mineral aerosol), smoke, soot and biologic (pollen, bacteria, algae, etc.). Secondary particles are formed in the atmosphere by transformation of gaseous compounds to the liquid or solid phase. These particles are composed primarily of sulfate, nitrate and oxy-hydrocarbons, which are produced by direct, catalytic, or photochemical oxidation of sulfur, nitrogen, and volatile hydrocarbons.

The determination of the aerosol size distribution is one of the most important parameters for characterizing the behavior of the aerosols in the atmosphere. The study of the aerosol size distributions assist in identifying their origin, chemical composition, atmospheric residence time, possible environmental effects of the aerosols (visibility reduction, cloud and fog formation, etc.) and adverse health effects [26,27]. The variations in size distribution of the aerosols strongly influence the radiative properties of the aerosol species such as the scattering-albedo and the spectral variation of the aerosol optical thickness [28]. In addition, atmospheric aerosols have a significant impact on cloud physics, because the small particles can act as cloud condensation nuclei [29–32].

The size distribution of the atmospheric aerosols may generally be described as containing three modes, as a function of the radius of the particle (assuming a spherical shape): the Aitken particles or the nucleation mode: $0.001 < R_p < 0.1\ \mu m$, the accumulation mode: $0.1 < R_p < 1\ \mu m$ and the coarse particle mode: $R_p > 1\ \mu m$ [33–35]. This classification has been commonly used in size distribution measurements, in the characterization of aerosol dynamics and are detailed in Whitby and Cantrell [36] and Whitby and McMurry [37].

The organic carbon (OC) and black carbon (BC) (major components of carbonaceous aerosols) have an impact on the regional and global climate and may also affect the human health and the local environment [38]. While organic carbon has both a primary and secondary origin, BC is essentially a primary pollutant emitted directly during the incomplete combustion of fossil and biomass carbonaceous fuels [39]. BC represents the principal fraction of the carbonaceous particles that account for the absorption properties of the atmospheric aerosols [40]. Therefore, an important consequence of the presence of BC in the atmosphere is the increased absorption of the solar radiation, which may be translated into a warming of the atmosphere while reducing solar irradiance at the ground, altering the vertical temperature profile. The effect of BC was recognized to be a significant indirect forcing on global-scale climate, but it was estimated with large uncertainties [41]. The increase in radiation absorption by water droplets containing dissolved BC particles may potentially decrease the cloud albedo [42,43] and this can affect substantially the indirect forcing of climate [44].

Webster et al. [45] developed specific emission scenarios with assumed probabilities and simulated future global climate projections over the next 100 years. Fig. 1 shows the projections for black carbon and organic carbon emissions [45]. Fig. 2 indicates black carbon concentrations originated from biomass burning during the dry season in Amazonia, Brazil [46]. Fig. 3 shows estimated fossil-fuel black carbon emissions from years 1825 to 2000 [40] and [47].

It is important to emphasize the biogenic aerosols because of the intense emissions that occur in the tropical rain forest [48–50]. The biogenic aerosols are composed both of primary and secondary aerosols. The mechanisms of biogenic emissions are still not well understood. These mechanisms may include mechanical abrasion by the wind action, biological activity of microorganisms on plant surfaces and forest litter, and physiological processes of plants as, for example, plant transpiration and guttation [48]. The primary biogenic aerosols are particles that can be produced by the dispersion and disintegration of animal and plant debris, and the dispersion of microbes into the atmosphere. Primary biogenic aerosols encompass many distinct types of particles that may be

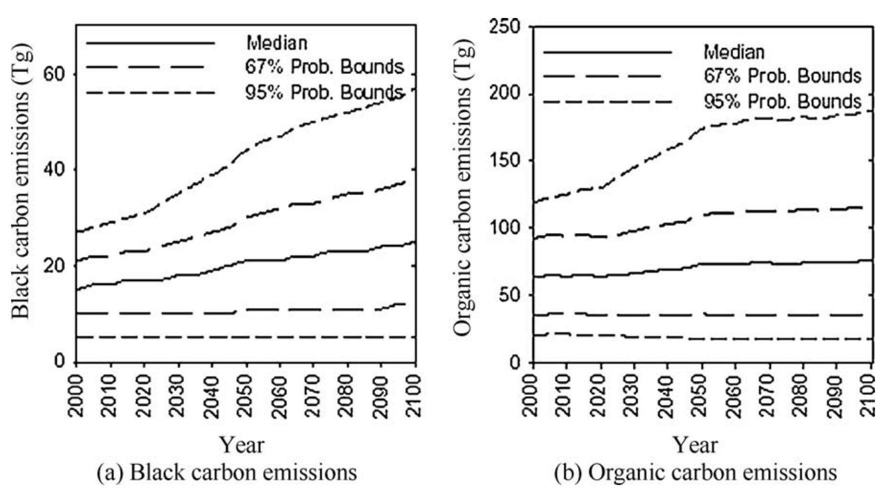


Fig. 1. Projected scenarios for future aerosol annual emissions not treated by the IPCC SRES: (a) black carbon and (b) organic carbon.Source: From Webster et al. [45].

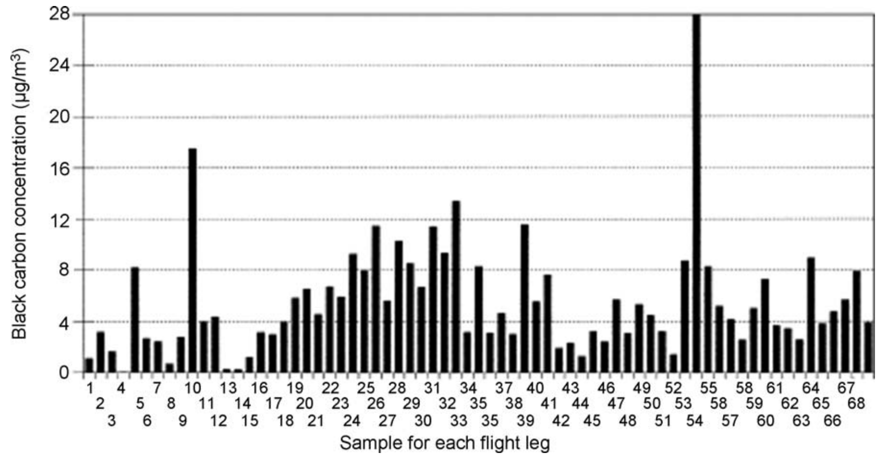


Fig. 2. Atmospheric aerosols in Amazonia: black carbon concentrations (aircraft sampling) in μg m^{-3} for each flight leg during the SCAR-B experiment.Source: From Artaxo et al. [46].

divided into living or nonliving particles. Living particles consist most of bacteria, fungi, algae, protozoa, pollen, spores, etc. Nonliving particles consist of plant debris (leaf fragments, cuticular waxes, etc.), excrement and fragments of insects, dead microbes, etc. [49]. In the forest environment, bacteria are the smallest of the primary biogenic particles, having diameters in the size range between 0.5 and 2.0 μm. These particles may act as cloud condensation nuclei (CCN) [50]. In this case, CCN modify the cloud droplet size distribution and, therefore, the reflectivity of the clouds [51,32]. The cytoplasm of some pollen is hygroscopic and it is able to act as CCN. Most of the other primary particles are much larger, and it is estimated that 20–30% of all aerosol particles larger than 4 μm in diameter have a biological origin. Secondary biogenic aerosols are formed in the atmosphere by gas-to-particle conversions of organic nitrogen and sulfur-related gas components which are released from forested areas [49]. Only higher hydrocarbons (C10–C28 n-alkanes) are candidates for forming aerosol particles.

An important global source of atmospheric aerosols is biomass burning (BB) over the tropics and equatorial regions during the dry seasons [52]. The characterization of the smoke from BB depends on the nature of the biomass as well as on the type, intensity, and smoldering and flaming phases of the fire [53]. Biomass burning is a significant primary source of soot (black carbon) and organic particulate matter which are emitted in the atmosphere. Fine mode particulates (smaller than 2 μm) constitute the largest portion of the aerosol from BB. Because of its small size, the aerosol from BB can be transported in the air for large distances and may remain suspended for up to one week [54]. These aerosols

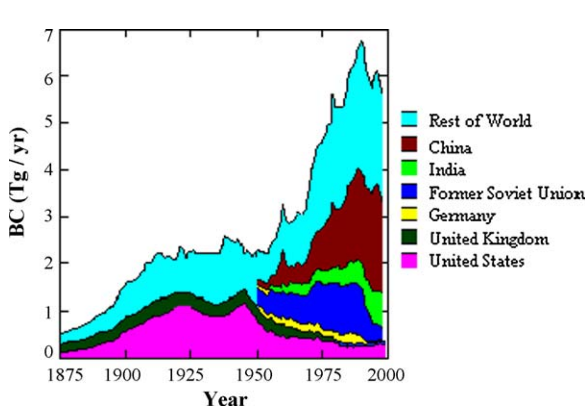


Fig. 3. Estimated fossil-fuel black carbon emissions.Source: From Novakov et al. [40] and Tegen et al. [47].

significantly reduce the local and regional visibility, scatter and absorb the incident solar radiation, may act as CCN and affect the albedo of the Earth [55,53]. Due to differences in the vegetation type in the source regions, both optical properties and emission factors show variability. Yamasoe et al. [52] performed experiments in the Amazon Basin. They found that the emission factors associated with tropical rain forest burning showed higher variability than emission factors from "cerrado" burning.

The significant increase in the BB smoke emissions verified in the last years, due to both controlled and wild fire, is recognized as a regional and global problem. Seasonal burning result mostly of the vegetation clearing (forest, grassland and savanna), in the tropics and sub-tropics, for converting forest into agricultural and pastoral lands, and for removing the vegetation in order to improve agricultural productivity and the growth of high yield grasses. This process significantly increases the input of organic aerosol components in the atmosphere. There is indication that BB smoke plumes should have a net cooling effect on the local and regional climate system, compensating that of a doubling of CO_2 in affected regions.

Anthropogenic aerosol emissions have long contributed to local, regional and global pollution. There are various mechanisms through which aerosols may affect climate. Three of them are of special importance: (i) heterogeneous chemical processes, in particular, the interaction of ozone molecules with the surface of aerosol particles [56], (ii) direct particle scattering and absorption, and (iii) indirect effects of the aerosols (alterations promoted in the cloud formation mechanisms) on the global radiation balance. However, there is a large uncertainty in the evaluation of the aerosol radiative forcing due to incomplete knowledge on several aerosol related factors as, for example: the quantification of sources and sinks, the composition and size distribution of the particulates, the chemical interaction processes that may take place, and their lifetime.

The indirect effects refer to the interaction between the aerosols and cloud droplets, which may cause modifications in their optical properties and lifetimes. They are related to changes in the cloud droplet size distribution resulting, in general, in more and smaller droplets due to the high availability of aerosols acting as cloud condensation nuclei (CCN) [57]. The CCN can influence the cloud albedo [8,58,59] and lead to the evolution and development of the precipitation process, particularly for deep convective clouds [60]. The CCN may also alter the hydrological cycle in tropical regions [61]. Myhre et al. [62] investigated the evolution of the radiative forcing for several mechanisms. Based on previous works available in the literature, they pointed out that the indirect aerosol effects

Table 1
Estimates of the indirect radiative forcing due to anthropogenic aerosol emissions.

Aerosol component	Mean global ($W\,m^{-2}$)	Reference
Troposphere		
Sulfate	−1.4 or −2.2	Lohmann and Feichter [58]
Top-of-the-atmosphere (TOA)		
Nitrate	−0.02	Bower et al. [71]
Sulfate	−1.3	Jones et al. [72]
Sulfate (relative to the pre-industrial era)	−1.33	Bower et al. [71]
Sulfate (over oceans) marine stratocumulus	−1.1	Kogan et al. [73]
Tropopause		
Anthropogenic aerosol (a)	−2	Takemura et al. [74]

Source: Authors based on the references cited; (a) anthropogenic aerosols from fossil fuel.

are possibly the most uncertain anthropogenic mechanisms involved in climate change, and that previous estimates yield to large variations of the obtained values. Table 1 shows global estimates for the indirect effect on radiative forcing due to the anthropogenic aerosol emissions.

The direct effect is related to the radiation budget in the surface–atmosphere system, through redistribution of shortwave solar radiation and infrared surface radiation, because atmospheric aerosols present in the atmosphere can scatter and absorb a significant fraction of the incoming solar radiation [33,56]. Many investigations on the direct effect of aerosols have focused their attention on sulfate particles, due to their importance as one of the main anthropogenic aerosols component [63–65]. Scattering and absorption by aerosol particles depend on their physical and chemical characteristics, and are the primary causes for decrease in visibility [66]. Table 2 shows global estimates for the direct radiative forcing due to anthropogenic aerosol emissions.

Table 2
Estimates for the direct radiative forcing due to anthropogenic aerosol emissions.

Aerosol component	Mean global ($W\,m^{-2}$)	Reference
Troposphere		
Sulfate	−1.3	Charlson et al. [44]
Sulfate	−0.3	Kiehl and Briegleb [9]
Sulfate	−0.34	Haywood and Shine [76]
Sulfate	−0.38	Haywood et al. [77]
Sulfate	−0.36	Myhre et al. [78]
Sulfate	−0.80	Haywood and Ramaswamy [79]
Sulfate	−0.65	Koch [80]
Soot/sulfate	−0.18	Haywood et al. [77]
Soot	+0.20	Haywood et al. [77]
Soot	+0.14	Myhre et al. [78]
Soot	+0.20	Haywood and Ramaswamy [79]
BC	+0.35	Koch [80]
OC	−0.30	Koch [80]
Mineral dust	+0.1	Tegen et al. [70]
Top-of-the-atmosphere (TOA)		
Sulfate	−0.8	Penner et al. [83]
Sulfate	−0.95	Adams et al. [81]
Biomass burning	−1	Penner et al. [82]
Biomass burning	−0.2	Penner et al. [83]
Soot	+0.20	Penner et al. [83]
Nitrate	−0.19	Adams et al. [81]
Black carbon (a)	+0.54	Chin [84]
Black carbon: industrial emission	+0.16	Chin [84]
Black carbon: BB emission	+0.38	Chin [84]
Tropopause		
Carbonaceous (OC + BC) (b)	−0.24	Takemura et al. [75]
Organic carbon (OC) (b)	−0.45	Takemura et al. [75]
OC: fossil fuel (b)	−0.09	Takemura et al. [75]
Biomass burning	−0.29	Takemura et al. [75]
Black carbon (b)	+0.21	Takemura et al. [75]
BC: fossil fuel (b)	+0.13	Takemura et al. [75]
BC: biomass burning (b)	+0.07	Takemura et al. [75]
Sulfate (b)	−0.72	Takemura et al. [75]
Sulfate: fossil fuel (b)	−0.57	Takemura et al. [75]
Soil dust (b)	+0.26	Takemura et al. [75]
Sea salt (b)	−0.59	Takemura et al. [75]

Source: Authors based on the references cited; (a) no mixing with other aerosols; (b) clear-sky conditions.

Scattering of the sunlight radiation back to space and changes in the cloud properties are expected to have a cooling effect [67]. However, the absorption of radiation by aerosols results in a heating of the atmosphere. However, few works have investigated the possible warming effects of aerosols [43,68]. Calculations of solar heating rates within climate models have been tuned to work with Rayleigh scattering, which is appropriate for gaseous species. The introduction of various aerosols and cloud droplets optical properties requires a reconsideration of the modeling approach (by using the Mie Theory) to accurately predict the associated radiative forcing [69]. The effect of anthropogenic aerosols is not limited to the cooling promoted by sulfate aerosols. In addition, carbonaceous compounds that include light-absorbing black carbon may be an important warming agent.

4. Conclusion and final comments

Proposals recently emerged in the international scientific literature about the production of a cooler effect in the Earth surface at short-term by injecting a large quantity of aerosol particles in the stratosphere like a "virtual volcano". The proposals are inspirited in the observed cooling of the atmosphere following two volcanic eruptions, El Chichon in 1984 and Mount Pinatubo in 1991. In 15 June 1991 a volcanic eruption of the Pinatubo Mount in Philippines resulted in around minus 0.5 °C in the average Earth surface temperature in 1992, and only in 1995 the temperature got back to the previous average value. According to the proponents, the idea of injecting sulfates into the stratosphere is defensible because of the dilemma of the global mean temperature increase, the difficulties to find an international solution for GHG emissions reductions in the short term, and because it could reduce global warming while there is more time for society to find ways for reducing the emissions of carbon dioxide.

Nevertheless, research's initiatives to consider whether it would be feasible to artificially enhance the albedo of the planet Earth to counteract greenhouse warming need to be deeply analyzed. Several regional and local environmental problems may result as consequences of these emissions.

Since the first considerations of the effects of aerosols on climate change, their importance in this arena has been growing steadily. It has been recognized that their interactions in the atmosphere may significantly alter the local energy balance. This may have not only a local influence but also a regional and global effect.

The aerosol effects depend on the type of source, on several aerosol properties (size distribution, concentration, optical properties, etc), as well as on the particulate ability to serve as cloud condensation nuclei (CCN) and interact with the cloud droplets. The later were referred to as the aerosol indirect effects. Radiative forcing from the aerosols may be positive (warming effect) or negative (cooling effect). In general, the indirect effects are associated with increased albedo, resulting in a negative radiative forcing. This may compensate and offset the effects of the emissions of greenhouse gases (GHG). Aerosols direct effects may either be responsible for negative (sulfate aerosols) or positive (black carbon—BC) radiative forcing. It also has been called the attention for the fact that by increasing the number of CCN above a

certain level the condensation process will in fact produce smaller droplets, which may evaporate back more easily.

The aerosols may be formed by primary or direct emissions, or they may be produced by gas-to-particle conversions, in which case they are termed as secondary aerosols. There are several important sources for aerosols all over the planet. These may be anthropogenic or natural. In most of the urban regions in developing and developed countries, one of the biggest sources of emissions is the transport sector. In developing countries, the emissions associated with biomass burning, for clearing areas for agriculture, may also be large. Forests may have a great impact in the emissions of biogenic natural aerosols.

Aerosols have a strong impact on the local/regional population health. This represents a strong burden for the local government. Although these aerosol emissions might offset the effect of the GHG, they increase the pollution of the atmosphere and should be avoided because of economic and social reasons. In this review paper we attempted to prove, from the analysis of several studies available in the literature, that despite the large number of different research trying to investigate the possible effects of aerosols on healthy and environment as a whole, there is a lot to be done before considering the idea of injecting sulfates into the stratosphere for the purpose of producing global and regional cooling effects.

References

[1] Crutzen PJ. Albedo enhancement by stratospheric sulfur injections: a contribution to resolve a policy dilemma. Climatic Change 2006;77:211–9.
[2] Wigley's TML. A combined mitigation/geoengineering approach to climate stabilization. Science)2006;(September 14).
[3] Bergtsson L. GEO-engineering to confine climate change: is it at all feasible? Climatic Change 2006;77:229–34.
[4] McCormick RA, Ludwig JH. Climate modification by atmospheric aerosols. Science 1967;156:1358–9.
[5] Schneider SH. A comment on "climate: the influence of aerosols". Journal of Applied Meteorology 1971;10:840–1.
[6] Rasool SL, Schneider SH. Atmospheric carbon dioxide and aerosols: effects of large increases on global climate. Science 1971;173:138–41.
[7] Twomey S. Pollution and the planetary albedo. Atmospheric Environment 1974;8:1251–6.
[8] Twomey S. Influence of pollution on the short-wave albedo of clouds. Journal Atmospheric Science 1977;34:1149–52.
[9] Joseph JH. Aerosols in a numerical model of the general circulation of the atmosphere. In: Fuller M, Johnston MJS, Yukutake T, editors. Seattle, Washington, U.S.A.: IAGA/IAMAP Joint Assembly; 1977;
Kiehl JT, Briegleb BP. The relative roles of sulfate aerosols and greenhouse gases in climate forcing. Science 1993;260:311–4
[10] Penner SS, Schneider AM, Kennedy. Active measures for reducing the global climatic impacts of escalating CO_2 concentrations. Acta Astronautica 1984;11:345–8.
[11] Laurmann JA. Scientific uncertainty and decision making: the case of greenhouse gases and global climate change. The Science of the Total Environment 1986;55:177–86.
[12] Grassl H, Newiger M. Changes of local planetary albedo by aerosol particles. The Science of the Total Environment 1982;23:313–20.
[13] Izrael YA. Energy development and its effect on the environment. Energy 1987;12:969–74.
[14] UNFCCC (United Nations Framework Convention on Climate Change). www.unfccc.int; 1992.
[15] Schwartz SE. Does fossil fuel combustion lead to global warming? Energy 1993;18:1229–48.
[16] Olmo FJ, Tovar J, Alados-Arboledas L, Okulov L, Ohvril HO. A comparison of ground level solar radiative effects of recent volcanic eruptions. Atmospheric Environment 1999;33:4589–96.
[17] Andronova N, Schlesinger M. Importance of sulfate aerosol in evaluating the relative contributions of regional emissions to the historical global temperature change. Mitigation and Adaptation Strategies for Global Change 2004;9:383–90.
[18] IPCC (Intergovernmental Panel on Climate Change). First, second, third and forth assessment reports, WGI. www.ipcc.ch; 2010.
[19] Tett SFB, Stott PA, Allen MR, Ingram WJ, Mitchell FB. Causes of twentieth-century temperature change near the Earth's surface. Nature 1999;399:572–96.
[20] Dehn M, Burna J. Modelling future landslide activity based on general circulation models. Geomorphology 1999;30:175–87.
[21] Schlesinger ME, Malyshev S, Rozanov EV, Yang F, Andronova, Vries B, et al. Geographical distributions of temperature change for scenarios of greenhouse gas and sulfur dioxide emissions. Technological Forecasting and Social Change 2000;65:167–93.
[22] Muzik I. A first-order analysis of the climate change effect on flood frequencies in a subalpine watershed by means of a hydrological rainfall–runoff model. Journal of Hydrology 2002;267:65–73.
[23] Wild M, Ohmura A. The role of clouds and the cloud-free atmosphere in the problem of underestimated absorption of solar radiation in GCM atmospheres. Physics and Chemistry of the Earth Part B Hydrology Oceans and Atmosphere 1999;24:261–8.
[24] Dobbie S, Li J, Harvey R, Chýlek P. Sea-salt optical properties and GCM forcing at solar wavelengths. Atmospheric Research 2003;65:211–33.
[25] Roberts DL, Edwards JM. General circulation model simulations of the direct climatic effect of anthropogenic sulfate aerosols. Journal of Aerosol Science 1995;26:S3.
[26] Salma I, Maso MD, Kulmala M, Záray G. Modal characteristics of particulate matter in urban atmospheric aerosols. Microchemical Journal 2002;73:19–26.
[27] Pohjola M, Pirjola L, Kukkonen J, Kulmala M. Modelling of the influence of aerosol processes for the dispersion of vehicular exhaust plumes in street environment. Atmospheric Environment 2003;37:339–51.
[28] Masmoudi M, Chaabane M, Tanré D, Gouloup P, Blarel L, Elleuch F. Spatial and temporal variability of aerosol: size distribution and optical properties. Atmospheric Research 2003;66:1–19.
[29] Novakov T, Penner JE. Large contribution of organic aerosols to cloud-condensation-nuclei concentration. Nature 1993;265:823–6.
[30] Cruz CN, Pandis SN. A study of the ability of pure secondary organic aerosol to act as cloud condensation nuclei. Atmospheric Environmental 1997;31:2205–14.
[31] Corrigan CE, Novakov T. Cloud condensation nucleus activity of organic compounds: a laboratory study. Atmospheric Environment 1999;33:2661–8.
[32] Roberts GC, Artaxo P, Andreae MO. The chemistry and role of cloud condensation nuclei in the Amazon basin. Journal of Aerosol Science 2000;31:62–3.
[33] Kokhanovsky AA. Phase function of atmospheric background aerosol at large scattering angles. Journal of Aerosol Science 1996;27:S557–8.
[34] Hering S, Eldering A, Seinfeld JH. Bimodal character of accumulation mode aerosol mass distributions in Southern California. Atmospheric Environment 1997;31:1–11.
[35] Clement CF, Ford IJ. Gas-to-particle conversion in the atmosphere. I. Evidence from empirical atmospheric aerosols. Atmospheric Environment 1999;33:475–87.
[36] Whitby KT, Cantrell B. Fine particles, international conference on environmental sensing and assessment. Las Vegas, NV: Institute of Electrical and Electronic Engineers; 1976.
[37] Whitby ER, McMurry PH. Modal aerosol dynamics modeling. Aerosol Science and Technology 1997;27:672–88.
[38] Gatari MJ, Boman J. Black carbon and total carbon measurements at urban and rural sites in Kenya, East África. Atmospheric Environment 2003;37:1149–54.
[39] Castro LM, Pio CA, Harrison RM, Smith DJT. Carbonaceous aerosol in urban and rural European atmospheres: estimation of secondary organic carbon concentrations. Atmospheric Environment 1999;33:2771–81.
[40] Novakov T, Ramanathan V, Hansen JE, Kirchstetter TW, Sato M, Sinton JE, et al. Large historical changes of fossil-fuel black carbon aerosols. Geophysical Research Letters 2003;30:1324–7.
[41] Penner JE, Charlson RJ, Hales JM, Laulaine N, Leifer R, Novakov T, et al. Quantifying and minimizing uncertainty of climate forcing by anthropogenic aerosols. Bulletin of the American Meteorological Society 1994;75:375–400.
[42] Chýlek P, Ramaswamy V, Cheng RJ. Effect of graphitic carbon on the albedo of clouds. Journal of the Atmospheric Sciences 1984;41:3076–84.
[43] Liu L, Mishchenko MI, Menon S, Macke A, Lacis AA. The effect of black carbon on scattering and absorption of solar radiation by cloud droplets. Journal of Quantitative Spectroscopy and Radiative Transfer 2002;74:195–204.
[44] Charlson RJ, Schwartz SE, Hales JM, Cess RD, Coakley Jr JA, Hansen JE, et al. Climate forcing by anthropogenic aerosols. Science 1992;255:423–30.
[45] Webster MD, Babiker M, Mayer M, Reilly JM, Harnisch J, Hyman R, et al. Uncertainty in emissions projections for climate models. Atmospheric Environment 2002;36:3659–70.
[46] Artaxo P, Campos RC, Fernandes ET, Martins JV, Xiao Z, Lindqvist O, et al. Large scale mercury and trace element measurements in the Amazon basin. Atmospheric Environment 2000;34:4085–96.
[47] Tegen I. Modeling the mineral dust aerosol cycle in the climate system. Quaternary Science Reviews 2003;22:1821–34.
[48] Artaxo P, Maenhaut W, Storms H, Van Grieken R. Aerosol characteristics and sources for the Amazon basin during the wet season. Journal of Geophysical Research 1990;95D:16971–85.
[49] Artaxo P, Hansson H. Size distribution of biogenic aerosol particles from the Amazon basin. Atmospheric Environment 1995;29:393–402.
[50] Gerab F, Artaxo P, Swietlicki E, Pallon J. Scanning proton microprobe applied to analysis of individual aerosol particles from Amazon Basin. Nuclear Instruments and Methods in Physics Research Section B Beam Interactions with Materials and Atoms 1998;136–138:318–23.
[51] Rogers CF, Hudson JG, Zielinska B, Tanner RL, Hallett J, Watson JG. Cloud condensation nuclei from biomass burning. In: Levine JS, editor. Global biomass burning, Proceedings of the Chapman conference on global biomass burning: atmospheric, climatic, and biospheric implications. Cambridge: MIT Press; 1991. p. 431–8.
[52] Yamasoe MA, Artaxo P, Miguel AH, Allen AG. Chemical composition of aerosol particles from direct emissions of vegetation fires in the Amazon basin: water-

soluble species and trace elements. Atmospheric Environment 2000;34: 1641–53.
[53] Simoneit BRT. Biomass burning—a review of organic tracers for smoke from incomplete combustion. Applied Geochemistry 2002;17:129–62.
[54] Nichol J. Bioclimatic impacts of the 1994 smoke haze event in SEA. Atmospheric Environmental 1997;31:1209–19.
[55] Oros DR, Simoneit BRT. Identification and emission factors of molecular tracers in organic aerosols from biomass burning. Part 1. Temperate climate conifers. Applied Geochemistry 2001;16:1513–44.
[56] Kondratyev KY. Greenhouse warming versus aerosol cooling in the context of global climate change. Energy Conversion and Management 1996;37:763–8.
[57] Nober FJ, Gras HF, Rosenfeld D. Sensitivity of the global circulation to the suppression of precipitation by anthropogenic aerosols. Global and Planetary Change 2003;37:57–80.
[58] Lohmann U, Feichter J. Impact of sulfate aerosols on albedo and lifetime of clouds: a sensitivity study with the ECHAM4 GCM. Journal of Geophysical Research 1997;102:12685–3700.
[59] Lohmann U, Feichter J, Chuang CC, Penner JE. Predicting the number of cloud droplets in the ECHAM GCM. Journal of Geophysical Research 1999;104:9196–8.
[60] Rosenfeld D, Lensky IM. Spaceborne sensed insights into precipitation formation processes in continental and maritime clouds. Bulletin of the American Meteorological Society 1998;79:2457–76.
[61] Crutzen PJ, Andreae MO. Biomass burning in the tropics: impact on atmospheric chemistry and biogeochemical cycles. Science 1990;250:1669–78.
[62] Myhre G, Myhre A, Stordal F. Historical evolution of radiative forcing of climate. Atmospheric Environment 2001;25:2362–73.
[63] West JJ, Hope C, Lane SN. Climate change and energy policy: the impacts and implications of aerosols. Energy Policy 1997;25:923–39.
[64] Omar AH, Biegalski S, Larson SM, Landsberger S. Particulate contributions to light extinction and local forcing at a rural Illinois site. Atmospheric Environment 1999;33:2637–46.
[65] Feczkó T, Molnár A, Mészáros E, Major G. Regional climate forcing of aerosol estimated by a box model for a rural site in Central Europe during summer. Atmospheric Environment 2002;36((September) 25):4125–31.
[66] Sloane CS. Optical properties of aerosols of mixed composition. Atmospheric Environment 1984;18:871–8.
[67] Kleefeld S, Hoffer A, Krivácsy Z, Jennings SG. Importance of organic and black carbon in atmospheric aerosols at Mace Head, on the West Coast of Ireland (53°19′N, 9°54′W). Atmospheric Environment 2002;36:4479–90.
[68] Sato M, Hansen JE, Koch D, Lacis A, Ruedy R, Dubovik O, et al. Global atmospheric black carbon inferred from AERONET. Proceedings of the National Academy of Sciences of the United States of America 2002;100:6319–24.
[69] Grant KE, Chuang CC, Grossman AS, Penner JE. Modeling the spectral optical properties of ammonium sulfate and biomass burning aerosols: parameterization of relative humidity effects and model results. Atmospheric Environment 1999;33:2603–20.
[70] Tegen I, Lacis AA, Fung I. The influence on climate forcing of mineral aerosols from disturbed soils. Nature 1996;380:419–22.
[71] Bower KN, Jones A, Choularton TW. A modelling study of aerosol processing by stratocumulus clouds and its impact on general circulation model parameterisations of cloud and aerosol. Atmospheric Research 1999;50:317–44.
[72] Jones A, Roberts DL, Slingo A. A climate model study of indirect radiative forcing by anthropogenic sulfate aerosols. Nature 1994;370:450–3.
[73] Kogan ZN, Kogan YL, Lilly DK. Evaluation of sulfate aerosols indirect effect in marine stratocumulus clouds using observation-derived cloud climatology. Geophysical Research Letters 1996;23(1):937–40.
[74] Takemura T, Okamoto H, Maruyama Y, Numaguti A, Higurashi A, Nakajima T. Global three-dimensional simulation of aerosol optical thickness distribution of various origins. Journal of Geophysical Research 2000;105(17):853–73.
[75] Takemura T, Nakajima T, Dubovik O, Holben BN, Kinne S. Single-scattering albedo and radiative forcing of various aerosol species with a global three-dimensional model. Journal of Climate 2002;15:333–52.
[76] Haywood JM, Shine KP. The effect of anthropogenic sulfate and soot aerosol on the clear sky planetary radiation budget. Geophysical Research Letters 1995;22:603–6.
[77] Haywood JM, Roberts DL, Slingo A, Edwards JM, Shine KP. General circulation model calculations of the direct radiative forcing by anthropogenic sulfate and fossil-fuel soot aerosol. Journal of Climate 1997;10(1):562–77.
[78] Myhre G, Stordal F, Restad K, Isaksen ISA. Estimates of the direct radiative forcing due to sulfate and soot aerosols. Tellus 1998;50B:463–77.
[79] Haywood JM, Ramaswamy V. Investigations into the direct radiative forcing due to anthropogenic sulfate and black carbon aerosol. Journal of Geophysical Research 1998;103:6043–58.
[80] Koch D. Transport and direct radiative forcing of carbonaceous and sulfate aerosols in the GISS GCM. Journal of Geophysical Research 2001;106(20):311–32.
[81] Adams PJ, Seinfeld JH, Koch D, Mickley L, Jacob D. General circulation model assessment of direct radiative forcing by the sulfate-nitrate-ammonium-water inorganic aerosol system. Journal of Geophysical Research 2001;106:1097–111.
[82] Penner JE, Dickinson RE, O'Neill CA. Effects of aerosol biomass burning on the global radiation budget. Science 1992;256:1432–3.
[83] Penner JE, Chuang CC, Grant K. Climate forcing by carbonaceous and sulfate aerosols. Climate Dynamics 1998;14:839–51.
[84] Chin, M.Black carbon aerosols: a burning question. Air Pollution as a Climate Forcing – a workshop. NASA Goddard Institute for Space Studies, University of Hawaii, Honolulu, Edited by Hansen, JE. http://www.giss.nasa.gov/meetings/pollution2002/d2_chin1.html, 2002.